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Longitudinal development of young talented speed skaters: physiological and anthropometric aspects

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de Koning, J. J., F. C. Bakker, G. de Groot, and G. J. van Ingen Schenau. Longitudinal development of young talented speed skaters: physiological and anthropometric aspects. *J. Appl. Physiol.* 77(5): 2311–2317, 1994.—A longitudinal analysis of a group of speed skaters was done to identify the performance-determining factors for a successful speed skating career. This paper presents both the physiological and anthropometric results of this longitudinal study. Twenty-four athletes from the Dutch National Junior Speed Skating Team were followed from age 16–17 yr to age 20–21 yr. During the development from junior to senior speed skater, a number of anthropometric and physiological variables changed. There were no differences between successful and unsuccessful speed skaters from an anthropometric perspective; consequently, it was not possible to distinguish successful from unsuccessful athletes on anthropometric grounds. The longitudinal data showed that at a younger age the successful speed skaters had similar oxygen consumption, mechanical efficiency, and power output values compared with the unsuccessful speed skaters. Later in the study, successful speed skaters distinguished themselves by the ability to produce higher power output values. There were no anthropometric or physiological relationships found in this study on which performance at the age of 20–21 yr could be predicted with measurements at a junior age.

oxygen uptake; power production; speed skating performance; anthropometry

EXCELLENCE in sport performance depends on many variables. Most of these variables can be categorized within the psychological, physiological, anthropometric, and biomechanical sciences. The objective of this study is to identify several performance-determining factors for speed skating by means of a longitudinal analysis of the development of a group of talented young speed skaters. This paper presents the results of physiological and anthropometric tests.

Speed skating can be described by an energy flow model (24). Such a model includes expressions that describe both the generation of mechanical energy from chemical substrates and the destination of the flow of energy. Both parts of the model have been shown to be influenced by internal and external variables such as skating technique, physique, and aerobic and anaerobic energy utilization (5, 6, 24, 31). These models are useful for the quantitative evaluation of the influence of physiological and anthropometric variables on the speed skating performance. Examples of the use of such models are found in the study of van Ingen Schenau et al. (31), which investigated the influence of body composition and race strategy on speed skating performance, and in the study of de Koning et al. (6), which described the influence of the aerobic and anaerobic energy pathways on sprint performance.

Various results from physiological and anthropomet-

ric testing of speed skaters can be found in the literature. Speed skaters can be characterized by these results as athletes with a well-developed aerobic capacity with maximal oxygen consumption ($\dot{V}O_{2\max}$) values ranging from 46.1 to 79.2 ml · kg⁻¹ · min⁻¹ (8, 16) and with an anaerobic power output, as measured during 30-s supra-maximal cycling, that belonged to the highest recorded by any group of athletes (25). Studies that focused on relationships between test results and speed skating performance show that significant correlation exists between $\dot{V}O_{2\max}$ and speed skating performance and between power output measured on a bicycle ergometer and speed skating performance (9–11). A review of the applied physiology of speed skating is given by de Groot et al. (3). Anthropometric aspects of speed skaters are described by Pollock et al. (20), van Ingen Schenau and de Groot (29), Sovak and Hawes (22), and Nemoto et al. (19). The results of these studies show that successful speed skaters are lean and have a higher fat-free mass than unsuccessful speed skaters.

On the basis of results presented in the literature (27), a protocol with two bicycle ergometer tests, meant to investigate the anaerobic and aerobic energy systems, and a series of anthropometric measurements were designed to analyze the development of talented young speed skaters during their progress from junior to senior speed skaters to identify anthropometric and physiological variables that determine speed skating performance.

METHODS

The research reported here is part of a 5-yr longitudinal investigation into the determinants of a successful career as a speed skater. Subjects were junior speed skaters who were either on the Dutch National Team or nominated for membership on the team. Physiological, anthropometric, and psychological data and data concerning speed skating technique were regularly collected (depending on the type of the variable being measured, 1–4 times/yr). The study started in the season of 1986/1987. Data were collected for the last time at the end of the season of 1990/1991.

Subjects. The study started in the season of 1986/1987 with 12 members of the Dutch National Junior Team and 6 speed skaters nominated for that team. The speed skaters were selected or nominated for the team on the basis of their skating performances during national and international competition. In the following years, young skaters were added to the National Junior Team and older skaters left for national senior teams or regional teams. Once elected to the Dutch National Junior Speed Skating Team, and therewith entering the study, the skaters were followed until the 1990/1991 season irrespective of their speed skating results. This gives information on the development of the speed skaters from age 16–17 yr to age 20–21 yr. All of the subjects were among the most successful junior speed skaters in the country when entering the study.

From the total group of subjects, 24 subjects participated ≥ 3 yr in the longitudinal study. The data of these skaters were

TABLE 1. *Best seasonal performances during first and last years of study*

	First Year		Last Year		Change	
	Success	No success	Success	No success	Success	No success
<i>Females</i>						
500 m, points	42.85±0.92*	44.21±0.65	42.01±0.74*	44.02±0.72	-0.85	-0.19
1,500 m, points	44.83±1.11	45.68±0.65	43.22±0.79*	45.02±0.69	-1.62†	-0.66
3,000 m, points	47.70±1.13	48.06±0.96	46.21±1.45	47.14±0.95	-1.48	-0.92
Total points	135.38±2.93	137.96±1.96	131.44±2.24*	136.18±2.25	-3.94†	-1.78
<i>Males</i>						
500 m, points	40.10±1.01	41.30±1.52	38.84±0.49*	40.17±1.18	-1.26†	-1.12
1,500 m, points	40.18±0.90*	41.93±2.03	38.51±0.59*	40.53±0.63	-1.68†	-1.40
5,000 m, points	43.44±1.12	45.64±1.43	41.68±1.20*	45.44±1.73	-1.75†	-0.20
Total points	123.73±2.87*	128.87±4.85	119.03±2.17*	126.14±2.69	-4.69†	-2.73

Values are means ± SD where indicated. Decrease in points indicates improvement in performance. * Significantly different compared with unsuccessful skaters, $P < 0.05$. † Significant change between first and last year values, $P < 0.05$.

used for the present study. The subjects gave their consent to participate in the study. At the end of the longitudinal study, it was possible to divide these 24 speed skaters into "successful" and "unsuccessful" groups based on their speed skating performances. All the speed skaters who represented the country at Olympic Games, World Championships, or European Championships during the course of the study were classified as successful, whereas the other speed skaters were classified as unsuccessful. The analysis of the data obtained from the athletes was done in four groups: 1) successful females, 2) unsuccessful females, 3) successful males, and 4) unsuccessful males. Each group contained six subjects.

For the purpose of this study, data of subjects collected during their first season in the longitudinal study were compared with data collected in their last season. The data were collected at comparable times during the different years of the study.

Physiological measurements. For testing the physiological characteristics of the speed skaters, two tests, a Wingate-type 30-s sprint test and a 2.5-min supramaximal test, were performed on an electrically braked bicycle ergometer (Mijnhardt) in a climate-controlled laboratory (17°C and 60% humidity). The 30-s sprint test was a Wingate-type test that the subjects had to perform in an all-out manner right from the start. The test was preceded by a warm-up consisting of submaximal cycling at 100 W interrupted by three short-lasting bursts of high intensity. After this warming-up, the subjects took a 2-min rest and concentrated on the upcoming maximal effort. During the tests, the subjects were vocally encouraged and continuously informed about the time that was remaining. The measured external power output was used to calculate peak power output and mean power output. After a 5- to 10-min cool-down period of cycling at 100 W, a rest of ≥45 min was taken before the supramaximal 2.5-min test was performed.

The warm-up for the 2.5-min test consisted of 3 min of cycling at 100 W and 3 min of cycling at 180 W. There was no rest between the submaximal warm-up and the 2.5 min of supramaximal cycling. The initial setting of the constant brake force on the flywheel of the ergometer is crucial for the outcome of both tests (27). Because all of the subjects were tested before, the individual brake settings could be determined on the basis of previous performances as well as on load setting recommended in the literature. During the 2.5-min test, the subjects were informed about their instantaneous power output and about the time that was left. Mean power output was calculated from the instantaneous external power output-time curves. Oxygen consumption ($\dot{V}O_2$) was measured for 30-s intervals during the warm-up and the actual test using an Oxycon-4 (Mijnhardt) gas analyzer. The external power and $\dot{V}O_2$ measured during the warm-up were used to calculate values for

efficiency. The bicycle ergometer and the gas analyzer were calibrated before each test.

Anthropometric measurements. The following anthropometric measurements were carried out by the same researcher on all subjects: 1) body mass and body length; 2) upper leg length (greater trochanter- knee joint cleft) and lower leg length (knee joint cleft-lateral malleolus); 3) girths of the upper leg 20 cm above the knee and at the gluteal fold; 4) biacromial breadth and chest girth at expiration; and 5) thicknesses of the triceps, biceps, subscapular, and suprailiac skinfolds. Measurements were made in triplicate, and the mean was used. From the four skinfold measurements, the body fat percentage was estimated according to Durnin and Womersley (7) and the lean body mass was calculated.

Speed skating performance. Speed skating performance is measured in the time needed to cover a certain distance. In speed skating, competition times are converted to points by expressing them into the time needed to cover each 500 m. For instance, a time of 120 s on a 1,500-m distance gives $120/(1,500/500) = 40.0$ points. Lower numbers indicate better performance than higher numbers. Performances over different distances can then be added to get a total performance in points. For the female speed skaters, the total performance is calculated by adding the points for the 500-, 1,500-, and 3,000-m distances, and for the male speed skaters, the total performance is calculated by adding the points for the 500-, 1,500-, and 5,000-m distances.

Treatment of data. To test differences in development between the successful and unsuccessful groups of subjects, changes in values of the different parameters over the course of the study were tested for significance using *t*-statistics (paired *t*-test). Differences between the groups were tested for significance with *t*-statistics as well. Correlation coefficients between the measured variables and performance as well as between changes in variables and changes in performance during the investigation were calculated. For all statistics, a significance level of $P < 0.05$ (two tailed) was used.

RESULTS

Performance. The best seasonal performances of the skaters, expressed in points, during the first year and last year of this investigation are shown in Table 1. It can be observed that successful skaters improved more (3–4%) during this period than unsuccessful skaters (1–2%). The difference between successful and unsuccessful performance in the last year was 3.6% for the female skaters and 6.0% for the male skaters.

TABLE 2. *Anthropometric variables in first and last years of study*

	First Year		Last Year		Change	
	Success	No success	Success	No success	Success	No success
<i>Females</i>						
Body length, cm	170.6±2.8	165.8±11.2	171.5±2.9	165.8±11.5	0.9	0.0
Body mass, kg	61.3±4.7	58.0±6.4	63.7±5.0	59.6±6.4	2.4*	1.6*
Body fat, %	20.4±3.6	22.0±1.5	21.0±3.7	22.0±2.0	0.5	0.1
Lean body mass, kg	48.7±2.6	45.2±4.8	50.2±1.9	46.5±5.1	1.5*	1.2*
Upper leg girth 1, cm	57.5±3.0	57.3±2.6	59.4±3.1	58.1±3.3	2.0*	0.8
Upper leg girth 2, cm	50.5±3.7	49.3±1.9	51.4±3.2	49.8±1.9	0.9	0.6
Upper leg length, cm	40.4±1.5	39.9±2.9	42.2±1.2	41.6±2.7	1.8	1.8
Lower leg length, cm	38.9±0.9	38.1±3.2	40.0±1.3	38.9±3.6	1.1	0.8
Biacromial breadth, cm	36.7±1.7	35.2±1.7	37.4±1.6	35.9±1.7	0.6	0.6
Chest girth, cm	73.9±3.2	73.5±2.3	73.9±3.4	74.1±2.2	0.0	0.6
<i>Males</i>						
Body length, cm	185.5±4.5	184.2±4.1	186.4±4.2	186.5±3.9	1.0	2.4
Body mass, kg	77.9±5.8	73.5±8.2	83.6±6.1	79.5±4.4	5.7*	6.0
Body fat, %	10.1±1.0	9.9±1.4	9.6±0.8	11.0±2.8	-0.5	1.1
Lean body mass, kg	70.1±5.5	66.2±6.5	75.6±5.9	70.7±3.9	5.5	4.6
Upper leg girth 1, cm	59.3±2.9	56.9±3.6	60.8±3.2	59.7±1.9	1.6	2.8*
Upper leg girth 2, cm	53.3±3.1	49.8±3.6	55.8±4.9	53.1±2.2	2.5*	3.2*
Upper leg length, cm	45.2±2.4	44.8±1.7	45.3±1.6	44.1±2.6	0.1	-0.6
Lower leg length, cm	44.1±2.8	43.7±1.7	44.6±3.7	44.1±1.5	0.4	0.4
Biacromial breadth, cm	41.1±1.2	41.1±1.3	42.0±1.7	42.2±1.5	0.8	1.1
Chest girth, cm	87.3±3.8	83.8±3.0	90.5±3.4	87.6±2.0	3.2*	3.8*

Values are means ± SD where indicated. * Significant change between first and last year values, $P < 0.05$.

Anthropometric results. Average values of the measured anthropometric variables are presented in Table 2. There was no difference in these variables between the successful and unsuccessful female as well as male skaters. During the period of this investigation, significant increases were seen in body mass, lean body mass, upper leg girth, and chest girth.

Physiological results. The results from the two bicycle ergometer tests are presented in Table 3. It seems impossible to distinguish successful skaters from unsuccessful skaters with the test results collected in the first year of this study. Outcomes of successful and unsuccessful athletes in the last year are only significantly different in a small number of the variables. The peak and mean power outputs during the 30-s test were higher for the successful than for the unsuccessful female speed skaters in the third year of this investigation. The only significant difference between successful and unsuccessful male speed skaters was the higher power output during the 2.5-min test for the successful skaters in the last year. Significant increases were observed in peak and mean power outputs on the 30-s sprint test for the successful as well as unsuccessful female speed skaters. The male speed skaters show an increase in power output during the 2.5-min test for the successful skaters, a decrease in power output during the 2.5-min test divided by body mass for the unsuccessful skaters, and a substantial increase in maximal $\dot{V}O_2$ for the successful skaters.

The results in Table 3 show that the normalization of power output values and $\dot{V}O_2$ to body mass or lean body mass does not help in the discrimination between successful and unsuccessful speed skaters.

Relevant correlation coefficients between certain variables and performance as well as between changes in certain variables and changes in performance during the investigation are given in DISCUSSION.

DISCUSSION

Speed skating performance. Despite the distinctive differences in performance between the successful and unsuccessful speed skaters, the total group of subjects in this study can be judged as rather homogenous compared with groups of subjects in former studies to differences between elite and subelite athletes (1, 4, 9–13, 29, 30). The difference in performance between successful and unsuccessful speed skaters in the last year of this study was 3.6 and 6% for females and males, respectively. These relatively small differences will lead to difficulties in detecting differences in anthropometric and physiological variables and restrict the conclusions of this study to groups of athletes of a rather high performance level.

During the time span of this study, an improvement in speed skating performance of the participating subjects took place. The female and male speed skaters who turned out to be successful improved significantly by 3 and 3.9%, respectively. The improvements of the female and male speed skaters who did not meet the criteria for being successful were not significant. The successful speed skaters participated with success in international championships and were among the top speed skaters of the world (some of them skated world records and won medals at the World Championships and Olympics).

In the first year of this study, the performances of the speed skaters who turned out to be successful were up to 4% better than those who turned out to be unsuccessful (Table 1). One could conclude from these differences that performance at the age of 17 is a good predictor for success 3–4 yr later, but if we look at the relationship between individual performance in the first year and in the last year of the study, only poor-to-modest correlation coefficients exist (females, $r = 0.31$; males, $r = 0.62$). This means that the prediction of individual speed skat-

TABLE 3. *Physiological variables during first and last years of study*

	First Year		Last Year		Change	
	Success	No success	Success	No success	Success	No success
<i>Females</i>						
P_{p30^*} , W	913.2±67.2	840.7±86.4	970.5±42.5*	892.3±91.9	57.3†	51.6†
P_{p30^*} /bm, W/kg	14.9±0.8	14.5±1.2	15.3±1.5	15.0±0.8	0.4	0.4
P_{p30^*} /lbm, W/kg	18.7±0.6	18.6±1.4	19.4±1.1	19.2±0.9	0.6	0.6
P_{m30^*} , W	692.7±56.0	641.4±65.1	742.5±33.0*	668.1±55.9	49.9†	26.7†
P_{m30^*} /bm, W/kg	11.3±0.7	11.1±0.8	11.7±1.1	11.3±0.8	0.4	0.2
P_{m30^*} /lbm, W/kg	14.2±0.6	14.2±0.9	14.8±0.8	14.4±1.0	0.6	0.2
$P_{m2'30^*}$, W	346.1±30.4	353.8±23.8	364.3±21.4	354.3±40.9	18.2	0.4
$P_{m2'30^*}$ /bm, W/kg	5.7±0.6	6.1±0.5	5.7±0.5	6.0±0.6	0.1	-0.2
$P_{m2'30^*}$ /lbm, W/kg	7.1±0.7	7.9±0.5	7.3±0.5	7.6±0.7	0.1	-0.2
$\dot{V}O_{2\max}$, l/min	3.23±0.15	3.17±0.24	3.32±0.23	3.23±0.26	0.09	0.06
$\dot{V}O_{2\max}$ /bm, ml·kg ⁻¹ ·min ⁻¹	52.9±4.6	54.9±3.8	52.2±2.4	54.5±4.1	-0.8	-0.5
$\dot{V}O_{2\max}$ /lbm, ml·kg ⁻¹ ·min ⁻¹	66.4±3.4	70.4±4.0	66.1±3.8	69.8±4.3	-0.3	-0.5
ME, %	23.5±1.2	23.8±1.0	22.2±1.8	22.3±1.5	-1.3	-1.5
<i>Males</i>						
P_{p30^*} , W	1,332.7±99.5	1,260.0±152.8	1,454.7±123.7	1,385.7±136.5	122.0	125.6
P_{p30^*} /bm, W/kg	17.1±1.2	17.2±0.9	17.4±0.7	17.4±1.3	0.3	0.3
P_{p30^*} /lbm, W/kg	19.0±1.4	19.0±1.0	19.2±0.8	19.6±1.2	0.2	0.5
P_{m30^*} , W	1,001.0±70.0	947.5±119.5	1,054.0±57.5	1,026.6±76.8	53.0	79.1
P_{m30^*} /bm, W/kg	12.9±0.9	12.9±0.7	12.6±0.5	12.9±0.8	-0.3	0.0
P_{m30^*} /lbm, W/kg	14.3±1.0	14.3±0.8	14.0±0.6	14.5±0.8	-0.3	0.2
$P_{m2'30^*}$, W	537.3±48.3	517.1±61.3	583.7±48.8*	530.4±47.6	46.4†	13.4
$P_{m2'30^*}$ /bm, W/kg	6.9±0.5	7.0±0.4	7.0±0.4	6.7±0.5	0.1	-0.4†
$P_{m2'30^*}$ /lbm, W/kg	7.7±0.5	7.8±0.4	7.7±0.4	7.5±0.5	0.0	-0.3
$\dot{V}O_{2\max}$, l/min	4.68±0.28	4.57±0.62	5.10±0.24	4.79±0.45	0.43†	0.23
$\dot{V}O_{2\max}$ /bm, ml·kg ⁻¹ ·min ⁻¹	60.1±3.0	62.0±2.6	61.2±2.9	60.2±3.4	1.0	-1.8
$\dot{V}O_{2\max}$ /lbm, ml·kg ⁻¹ ·min ⁻¹	66.9±3.5	68.9±3.3	67.7±3.5	67.7±4.0	0.7	-1.1
ME, %	20.6±2.7	22.1±1.8	18.6±0.8	19.8±2.7	-2.0	-2.3

Values are means ± SD where indicated. P_{p30^*} , peak power output during 30-s test; P_{m30^*} and $P_{m2'30^*}$, mean power output during 30-s and 2.5-min tests, respectively; bm, body mass; lbm, lean body mass; $\dot{V}O_{2\max}$, maximal O_2 consumption; ME, mechanical efficiency. * Significantly different compared with unsuccessful skaters, $P < 0.05$. † Significant change between first and last year values, $P < 0.05$.

ing performance later in the career appears not possible with the skating performance at a younger age.

Anthropometric variables. From an anthropometric perspective, the successful and unsuccessful athletes in this study are similar. None of the variables listed in Table 2 is significantly different between the two groups. Does this mean that the way the body is built has no influence on speed skating performance? Model calculations show the contrary (24, 31). Excessive amounts of body fat can influence the speed skating performance considerably, because speed skating performance depends on the power production by muscles as well as on the power losses to friction. A body composition with a high percentage of body fat increases the amount of energy lost to ice and air friction by the excessive weight and larger frontal area, which is not compensated by power produced with active body mass. Model calculations show that 1 kg in excessive body weight counts for 0.12 points for each distance. The results of this study show, however, that the differences in percentage of body fat (Table 2) between the successful and unsuccessful skaters are small.

The influence of body length and body mass on speed skating velocity was investigated by van Ingen Schenau (24). From an aerodynamic point of view, it can be assumed that small and light skaters have the advantage of a smaller air and ice friction compared with tall and heavy skaters. Tall and heavy skaters, however, are able to produce a higher power output if we assume that body

composition is not altered by higher body mass. Model calculations show that the increased frictional losses of tall speed skaters are completely cancelled out by their larger ability to produce power (26) and the advantage that they have in skating the curves (2). Regarding body mass and body length, it appears that an ideal build for a speed skater seems not to exist. This can explain the lack of differences between the successful and unsuccessful speed skaters with respect to these variables in our study.

Pollock et al. (20) compared male speed skaters who made the United States Olympic Team with skaters who did not succeed. They found that successful skaters were taller with a higher body mass and a higher lean body mass. The values for these three variables (180.0 cm, 72.8 kg, and 67.8 kg) obtained from the successful male skaters in the study of Pollock et al. are smaller than those for successful male speed skaters in our study. Sovak and Hawes (22) compared international-level speed skaters with physical education students. The most relevant difference between the speed skaters and the students is revealed in the relative and absolute larger amounts of muscle for the speed skaters. Compared with the skaters in their study, our successful male skaters appear to be larger and heavier in body mass and lean body mass, whereas our successful female skaters are similar in body mass and lean body mass but are taller. With respect to the dimensions of the upper body (biacromion breadth and chest girth), the skaters in our investigation are not different from the subjects in the

study of Pollock et al. and Sovak and Hawes. An exceptionally well-developed thigh distinguishes speed skaters from students in the study of Sovak and Hawes. For both male and female speed skaters in our study, the girth of the thigh was even larger. The well-developed thigh together with relationships between leg volume and peak power output reported by Winter et al. (32) and Mercier et al. (17) reflect the specificity of the training of speed skaters that is oriented toward the development of strength and endurance of the hip and knee extensors. However, even the unsuccessful groups of our study appear to meet these requirements.

In a comparison between elite and trained male speed skaters, van Ingen Schenau et al. (29) found that elite skaters have relatively shorter upper leg and longer lower leg lengths than the trained skaters. They stated that the relative shorter upper legs can be advantageous, since a shorter upper leg will require less muscle force of the extensors of the hip and knee joint in maintaining the skating position. This observation cannot be confirmed with the results of our study. We found no differences between successful and unsuccessful speed skaters regarding leg lengths and relative leg lengths (lower leg length divided by total leg length). The values for relative leg length of our study fall between the values reported for elite and trained subjects in the study of van Ingen Schenau et al. One of the possible reasons we are not able to confirm their findings is the much larger difference in performance between the elite and trained speed skaters in their study (17%) compared with the difference between the successful and unsuccessful speed skaters in our study (3.6 and 6%).

From the almost constant length measurements obtained in the first and last years of this study, it can be concluded that the speed skaters had reached their mature length before they entered the study. The increases in body mass monitored during the course of the study can presumably be ascribed to increases in the mass of thigh muscles, since the percentage of body fat is constant and the lean body mass and thigh girth are increased during the study. There is no difference observed in the development of anthropometric variables between the successful and unsuccessful speed skaters.

The only significant correlation between anthropometry and performance is found for the lean body mass of the males ($r = -0.61$). The correlations between the change in lean body mass and the change in time to complete a race as recorded during this longitudinal study were $r = -0.84$ and $r = -0.40$ for males and females, respectively. This means that for the males a significant part of the increase in performance during the study coincides with their increase in lean body mass. The relationships between performance and chest girth, upper leg length, and thigh girth in middle-distance running as reported by Tanaka and Matsuura (23) are not present in our study, although the chest girth and thigh girths were increasing, especially for the male speed skaters.

From the anthropometric measurements, it can be concluded that it is not possible to distinguish successful from unsuccessful athletes when the differences in performance are as small as those in our study. Similar results were found in a study of factors associated with elite

endurance cycling (1), where performance differences of 10% were not large enough to find differences in anthropometric variables.

Physiological variables. Power output values as determined in speed skating competitions (24) show that in almost all of the events the required power output to accelerate and maintain speed is higher than the maximally released aerobic power output (6, 31). This means that part of the energy production must be done by the anaerobic energy system. From calculations based on measurements of the anaerobic kinetics in speed skaters, it can be concluded that the amount of anaerobic work at the different skating distances ranges from 82% for skating 500 m to 32% for skating 5,000 m (31). For this reason, two tests with a high anaerobic component were selected to follow the development of the young talented speed skaters in this investigation.

The results in Table 3 show that, regarding the variables measured on the bicycle ergometer, there are no differences between the successful and unsuccessful female and male speed skaters in the first year of this study. The performance differences of 1.9 and 4.2% for the female and male speed skaters, respectively, which correspond to a difference in power production during speed skating of 6 and 13% (24), are presumably not large enough to induce significant differences in physiological variables measured during cycling. Even in the last year of the study, limited variables were significantly different between successful and unsuccessful speed skaters. The female subjects showed a difference of ~10% between the successful and unsuccessful skaters in peak and mean power outputs as measured during the 30-s sprint test, whereas the male skaters exhibited a 10% difference in mean power output as obtained from 2.5-min supra-maximal tests. With these results, a part of the difference in power output during skating (11 and 19% for female and male skaters, respectively) associated with the respective 3.9 and 6.0% higher speed of skating can be explained. These findings are in agreement with findings of Foster et al. (9, 10) and Geysel et al. (11), who found that power output measured during a Wingate test was related to speed skating performance.

The physiological changes during the development from junior to senior speed skater are in certain variables different for female than for male skaters. The female speed skaters, both successful and unsuccessful, demonstrate a significant increase in power output during the 30-s test, whereas the successful male skaters increased their power output during the 2.5-min test by 8.6% and their maximal $\dot{V}O_2$ by 8.9%. The larger increase in power output and $\dot{V}O_2$ found for the successful male speed skaters are probably associated with the larger enhancement in performance of the successful compared with the unsuccessful male speed skaters during the course of this study. Note that all significant differences between the successful and unsuccessful speed skaters and the significant changes from the first to last year of this study occur in the nonnormalized values.

van Ingen Schenau and de Groot (28) determined that velocity of skating is dependent on the power output per kilogram body mass and suggested that $\dot{V}O_2$ and power output must be normalized to body mass. In this study,

none of these normalizations increased the predictive value of the power output or $\dot{V}O_{2\max}$ measurements, which is in line with the results reported by Foster et al. (9, 10).

From the longitudinal studies of Rusko (21) and Ingjer (14), it can be concluded that the development of $\dot{V}O_{2\max}$ in young athletes subjected to severe aerobic training happens before the age of 17 yr. After the age of 17 yr, $\dot{V}O_{2\max}$ expressed in milliliters per kilogram per minute reaches a plateau, $\dot{V}O_{2\max}$ expressed in milliliters per kilogram raised to the two-thirds power per minute is increasing slightly, and significant increases still occur in $\dot{V}O_{2\max}$ expressed in liters per minute. Our data of the successful male speed skaters show a similar development in $\dot{V}O_{2\max}$ values as the cross-country skiers in the study of Ingjer (14). Identical to these cross-country skiers, our speed skaters show a continuous improvement of performance at ages when the maximal aerobic power is at a plateau. These changes cannot be explained by changes in mechanical efficiency, as can be seen in Table 3.

The peak and mean power outputs of the speed skaters in our study show increases from the age of 16–17 yr to the age of 20–21 yr (significant for the females only). The power outputs related to body mass and lean body mass were not changing during the study. The very high power output values found in this study together with the well-developed thigh muscles of our subjects and the significant correlation coefficient between lean body mass and peak power output ($r = 0.83$ for both males and females) are arguments in favor of the findings of Mercier et al. (17), who found that significant correlations exist between leg volume and peak power and between total muscle mass and peak power.

A number of studies about the differences between successful and unsuccessful speed skaters are presented in the literature. de Koning et al. (4) found differences in joint moments and joint power output determined with inverse dynamics. van Ingen Schenau et al. (30) showed significant differences between successful and unsuccessful speed skaters in power output and $\dot{V}O_{2\max}$, measured with a 3-min supramaximal bicycle test, and a significant difference in $\dot{V}O_{2\max}$ during maximal speed skating. The difference in power output is in agreement with the findings of our study, but significant differences in $\dot{V}O_{2\max}$ are not. This is probably due to the larger differences in performance level between the successful and unsuccessful subjects in the study of de Koning et al. and van Ingen Schenau et al. (10 and 17%, respectively) compared with those in the present study (2–6%). Another reason for the smaller differences in our study may be the fact that the successful and unsuccessful groups of skaters were following the same training schedule. The study of Nemoto et al. (18) of successful and unsuccessful Japanese speed skaters with a difference in performance of 3% show only differences in $\dot{V}O_{2\max}$ expressed in liters per minute. Parameters related to the aerobic and anaerobic threshold were not different between elite and trained subjects in the study of Nemoto et al. The only difference found by Maksud et al. (15) between United States Olympic Team members and skaters who failed to make the team was for $\dot{V}O_{2\max}$ in liters per minute. From these studies, as well as from the study of Foster et al. (9, 10), it

can be concluded that the differentiation between successful and unsuccessful speed skaters should most likely be done with absolute $\dot{V}O_{2\max}$ values instead of values related to body mass.

Significant correlations between physiological variables and performance were only found with the results of the 30-s bicycle test. In the first year of the study, correlation coefficients between performance and peak power output were $r = -0.74$ and $r = -0.58$ for females and males, respectively. The same correlation in the last year of the study was not significant ($r = -0.44$ and $r = -0.26$ for females and males, respectively). The correlation between mean power output and performance was only significant for the females in the first year ($r = -0.68$). Significant correlations between peak power output measured in sprint tests and performance are reported for other sports as well. For 1,000-m time-trial cycling, Graig et al. (12) reported correlation coefficients of $r = -0.67$ and $r = -0.85$ between needed time and peak power output and total work, respectively, whereas Hawley and Williams (13) observed high correlation coefficients of $r = -0.82$ and $r = -0.83$ between 50-m swimming performance and peak as well as mean power output measured with an arm crank test, respectively. The correlations found in our study are smaller than those reported in the literature. This is mainly due to the larger range in performance, up to 33% performance difference between the best and the worst athlete, in the studies of Graig et al. and Hawley and Williams. A previous study done with speed skaters (11) showed similar high coefficients regarding power output and performance, but a lack in performance uniformity of the athletes makes these relatively strong correlations useless for the prediction of performance in a more uniform group of elite athletes. There are no significant correlations between the measured physiological variables at the age of 16–17 yr and performance at the age of 20–21 yr in the present study; this makes the prediction of performance at a senior age based on the chosen variables in this study, obtained at a junior age, not possible.

Conclusions. During the time span of this longitudinal study, an improvement in speed skating performance of the participating subjects took place. It can be concluded that the prediction of performance later in the career appears not possible based on performances at a younger age. During the development from junior to senior speed skaters, a number of anthropometric and physiological variables changed. There were no differences between successful and unsuccessful speed skaters from an anthropometric perspective; consequently, it was not possible to distinguish successful from unsuccessful athletes on anthropometric grounds. The longitudinal data showed that at a younger age the successful speed skaters had similar values on the measured physiological variables as the unsuccessful speed skaters. Later in the study, successful speed skaters distinguished themselves by the ability to produce higher power output values. There were no anthropometric or physiological relationships found in this study on which performance at the age of 20–21 yr could be predicted with measurements at a junior age.

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